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Time-resolved adaptive FEM simulation of the DLR-F11 aircraft model at high Reynolds number

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Main ingredients of our paper

Objective

...we would like to ***present a new methodology*** *for computational aerodynamics, and we would like this methodology to* ***establish a new direction*** *for the field.*

How to achieve that? (or "Road map" to presentation)

- Show quantitatively good/excellent results.
- Present main features of the method.
- Show hard figures of computational costs.

Key results I, lift breakdown

Case 2b / config4 / Re=15.1M

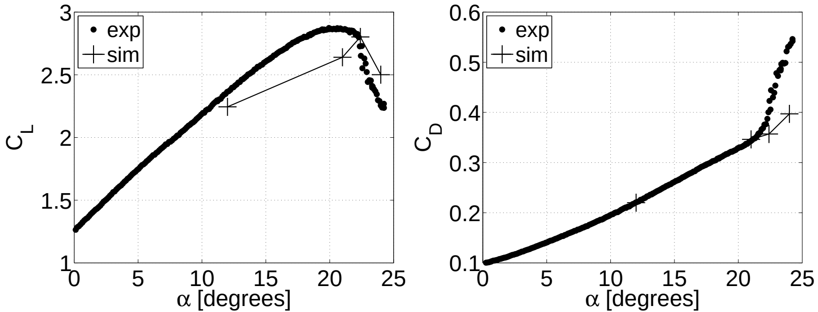


Fig: C_L, C_D, vs. angle of attack.

- Lift breakdown observed but no significant increase in drag.
- ...

Key results I, lift breakdown

Case 2b / config4 / Re=15.1M

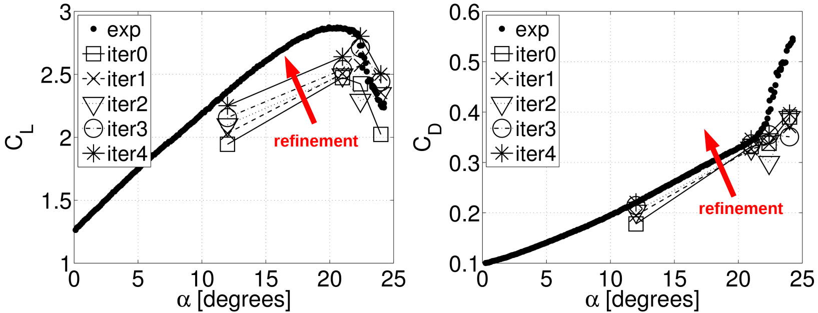


Fig: C_L, C_D, vs. angle of attack.

- Lift breakdown observed but no significant increase in drag.
- Refined result “approaches” measurements.

Key results II, stall prediction

Case 2b+3b / config4+config5 / Re=15.1M

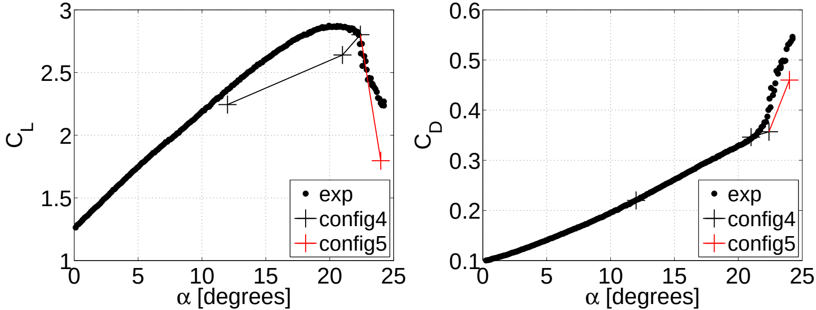
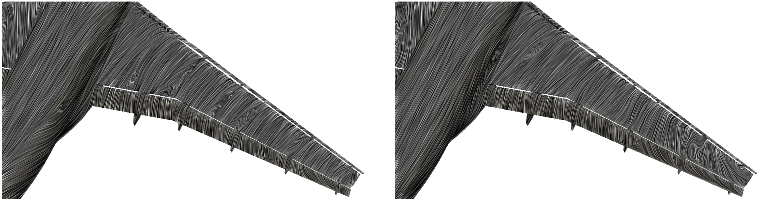


Fig: C_L, C_D, vs. angle of attack.

- "config4", angle of attack $\alpha = 12^\circ, 21^\circ$ and 22.4°.
- "config5", angle of attack $\alpha = 24^\circ$.
- Lift breakdown observed AND significant increase in drag for "config5", angle of attack $\alpha = 24^\circ$.

Key results II, stall prediction

Case 2b+3b / config4+config5 / Re=15.1M



config4 *config5*

Fig: Surface streamlines.

- Similar patterns along the wing.
- Stall cells growing towards the wing tip of “config5”.

Key results, summary

Case 2b / config4 / Re = 15.1M

- lift breakdown...
- ...BUT no clear increase in drag! Worse match to experiments...

Case 3b / config5 / Re = 15.1M

- lift breakdown...
- ...AND clear increase in drag! Better match to experiments...

Conclusion

Need full geometry (config5) to correctly predict experimental results.

Method highlights, DFS[1]

The General Galerkin method (G2)

- **FEM** with piecewise linear approximation in space and time.
- Fully **unstructured meshes**.
- **Time-resolved method** where **numerical stabilization** based on the residual dissipates turbulent kinetic energy.
- **Slip velocity boundary condition** with small (zero) skin friction.
- **Adaptive mesh refinement** with respect to output of interest using associated adjoint problem to estimate errors in output.

[1] Direct Finite Element Simulation

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Method highlights, DFS

In other words

- Unstructured meshes $\sim$ **solve problems with complex geometries**.
- Time-resolved method $\sim$ **no turbulence modeling**.
- Slip velocity boundary condition $\sim$ **no boudary layer mesh**.
- Adjoint-based adaptive mesh refinement $\sim$ **cells put on the right place, fewer cells, cheaper**.

Method highlights, DFS

For $\hat{U} = (U, P)$ a weak solution, $\hat{\varphi} = (\varphi, \theta)$ a solution to a linearized adjoint problem, and $M(\hat{U}) = ((\hat{U}, \hat{\psi}))$ a mean value output, with $\hat{\psi}$ a weight function, we define the error estimate:

$$\boxed{|M(\hat{u}) - M(\hat{U})| = |((\hat{u} - \hat{U}, \hat{\psi}))| \leq \sum_{K \in \mathcal{T}_n} \mathcal{E}_K,}$$

with the error indicator:

$$\mathcal{E}_K \equiv \sum_{n=1}^{N} \left[\int_{I_n} |R_1(\hat{U})|_K \cdot \omega_1 \, dt + \int_{I_n} |R_2(U)|_K \, \omega_2 \, dt + \int_{I_n} |SD_\delta^n(\hat{U}; \hat{\varphi})_K| \, dt \right],$$

for each element K in the mesh $\mathcal{T}_n$, with stability weights ω_i, $i = 1, 2$.

Method highlights, DFS

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for each element K in the mesh $\mathcal{T}_n$, with stability weights ω_i, $i = 1, 2$.

Method highlights, DFS

How do we generate the mesh?

Adaptive algorithm

1. For the mesh $\mathcal{T}_n$: compute primal and adjoint problem.
2. Compute error indicator for all cells
3. Mark 10% of the elements with highest "error indicator" for refinement.
4. Generate the refined mesh $\mathcal{T}_{n+1}$, and goto 1.

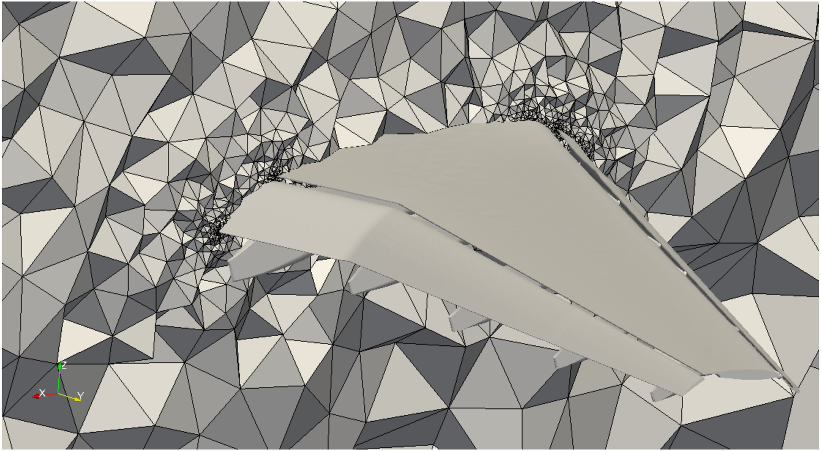
Initial mesh (angle of attack 12 $^\circ$):
3.8M cells

Final mesh (after 4 adaptive refinements):
22.6M cells

$\Rightarrow$ Compare, e.g., with committee's medium mesh, 99M cells for half airplane!

Method highlights, DFS

How do we generate the mesh?



Method highlights, DFS

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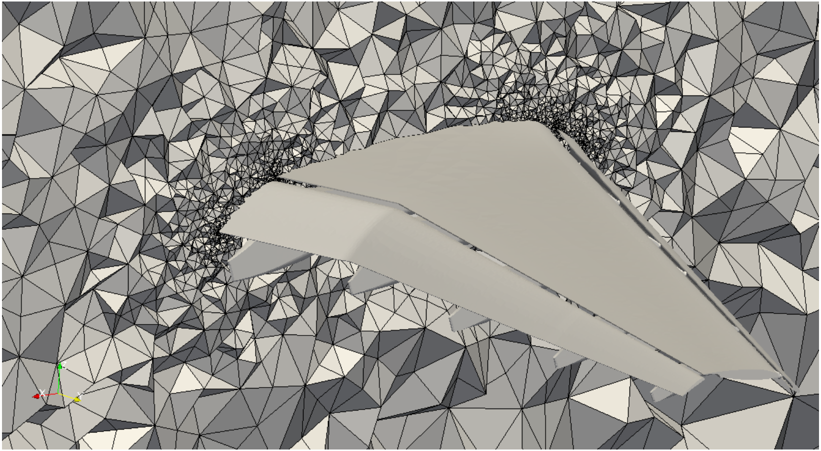

Method highlights, DFS

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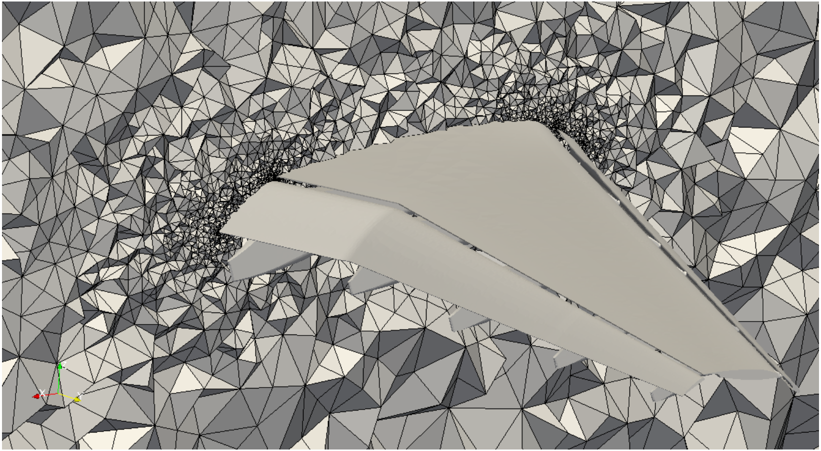

Method highlights, DFS

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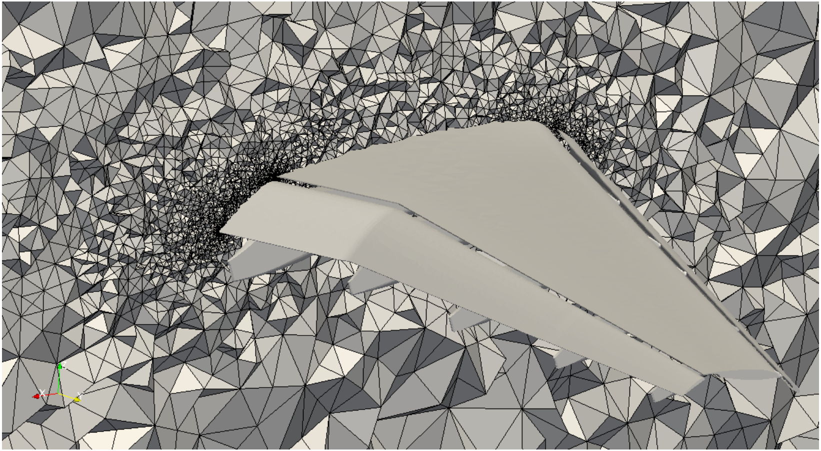

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Method highlights, DFS

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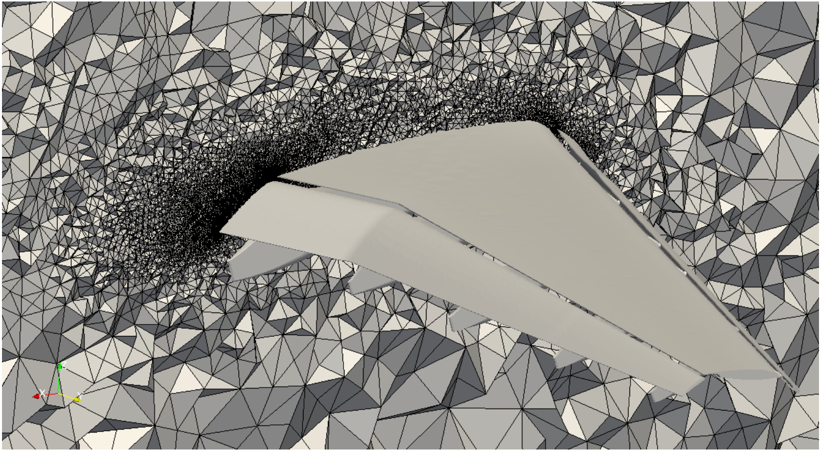
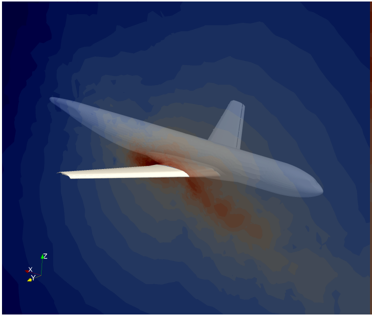
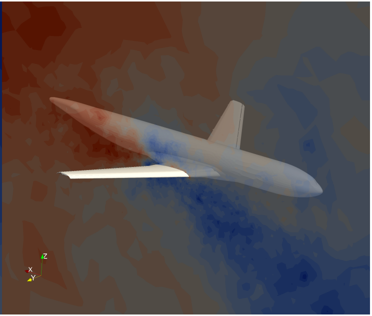


Method highlights, DFS

How adjoint adaptivity works



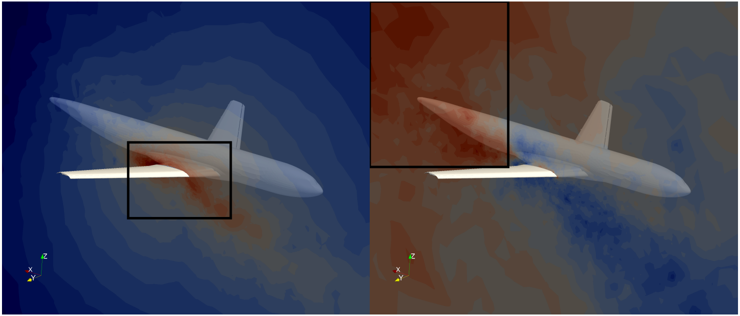
Adjoint velocity.



Momentum residual.

Method highlights, DFS

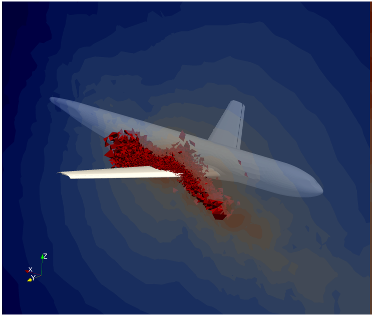
How adjoint adaptivity works



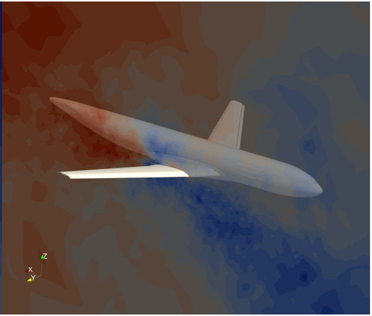
Adjoint velocity. *Momentum residual.*

Method highlights, DFS

How adjoint adaptivity works



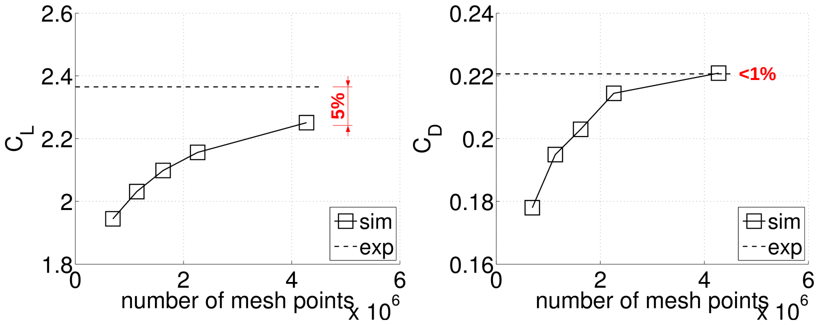
Marked cells refinement.



Adjoint velocity.

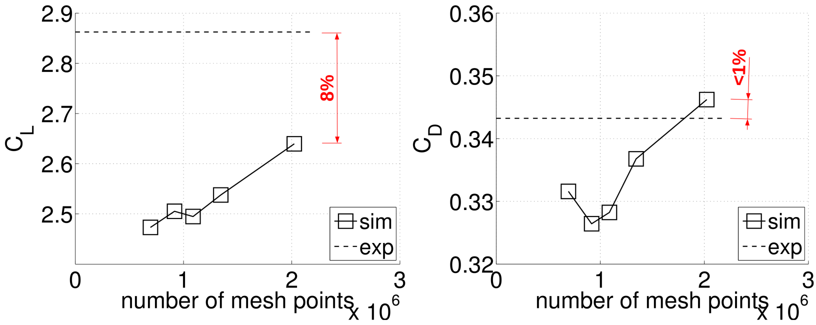
More results, convergence

Case 2b / config4 / Re=15.1M / Angle of attack 12 °



More results, convergence

Case 2b / config4 / Re=15.1M / Angle of attack 21 °



Computational resources

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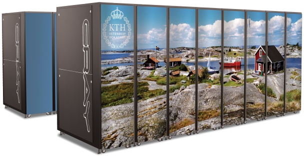
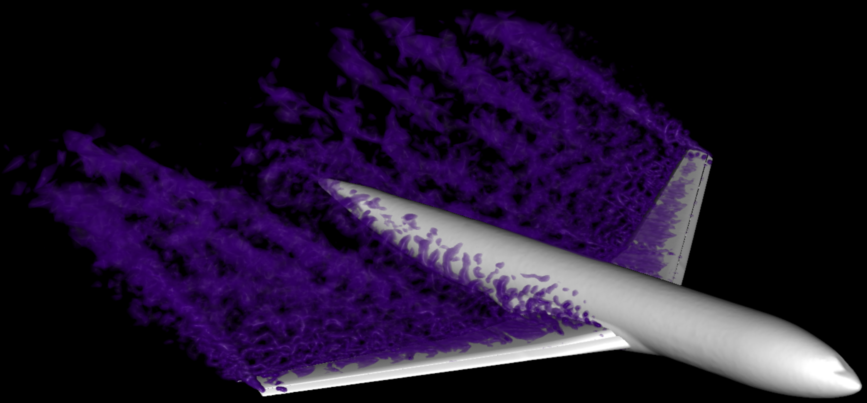
Lindgren at PDC/KTH

- 1,516 node Cray XE6.
- Dual 12-core nodes (36,384 cores).
- 32 GB DDR3 per node.
- Cray Gemini (3-D Torus topology).



Simulation time

- $200,000$ core hours (adaptive algorithm for 1 angle of attack).
- $800,000$ all simulations (12°, 21°, 22.4° and 24°.).
- Roughly 1 month on 1,000 cores.



Conclusions

We were able to compute the flow around a full aircraft model at high Re...

- ...stall prediction for config5.
- ...adaptive solution approaches experimental values.
- ...without boundary layer.
- ...with a time-dependent method.
- ...with fewer cells than anybody else.
- ...with (our own) open-source software.

Next, we would like to...

- ...perform further simulations with config5.

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Unicorn, DOLFIN @ open-source FENiCS-project

http://dryad.csc.kth.se/projects/dolfin-hpc/files
http://dryad.csc.kth.se/projects/unicorn-hpc/files
http://www.fenicsproject.org/

Acknowledgements

Initial mesh generated with **ANSA** by Beta CAE Systems.

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- Swedish Research Council, Swedish Energy Agency

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